

Experimental Results on p(d)+A Collisions at RHIC and the LHC

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Abstract

Recent experimental results at both the LHC and RHIC show evidence for hydrodynamic behavior in proton-nucleus and deuteron-nucleus collisions ($p+A$). This unexpected finding has prompted new measurements in $p+A$ collisions in order to understand whether matter with similar properties is created in $A+A$ and $p+A$ collisions or whether another explanation is needed. In this proceedings, we will discuss the new experimental data and its interpretation within the context of heavy-ion collisions.

Keywords:

1. Introduction

Collisions of protons or deuterons with large nuclei (hereafter collectively referred to as $p+A$ collisions) were studied as control measurements for heavy-ion collisions. Results since Quark Matter 2012 have cast doubt on this paradigm. The possible creation of hot nuclear matter has been suggested by measurements of long range azimuthal correlations in $p+Pb$ collisions at the LHC and $d+Au$ collisions at RHIC. These observations have motivated an abundance of v_N and spectra measurements in small collision systems to determine to what extent a hydrodynamic description is applicable in $p+A$. Additionally, significant modifications to jets and high- p_T hadrons have been observed at the LHC which remain unexplained. In this proceedings we discuss a selection of the interesting experimental results related to $p+A$ physics and highlight some of the open questions and new measurements that are needed.

The results discussed here are divided into three sections: high- p_T jets and hadrons, identified particles, and correlations.

2. High- p_T Jets and Hadrons

One of the original motivations for $p+A$ physics at RHIC and the LHC is to quantify nuclear modifications to the production of hard observables as a baseline for heavy-ion measurements. First results measurements of high- p_T single hadron production in both $d+Au$ [1, 2] and $p+Pb$ [3] were consistent with binary scaled $p+p$ to $p_T \approx 10$ GeV/c at RHIC and to ≈ 20 GeV/c at the LHC. New results presented at this conference show that reconstructed jet spectra are approximately consistent with binary scaling to very high p_T [4, 5, 6]. There is evidence for a slight excess of the nuclear modification factor, R_{pPb} , ($< 20\%$ at midrapidity) which is consistent with expectations from nuclear modifications to the parton distribution functions [7].

Surprisingly, single charged hadrons with $p_T > 30$ GeV/c show a large and significant excess compared to binary scaling of $p+p$ data (up to approximately a 40% increase) in recent measurements from the CMS [5] and ATLAS [8]

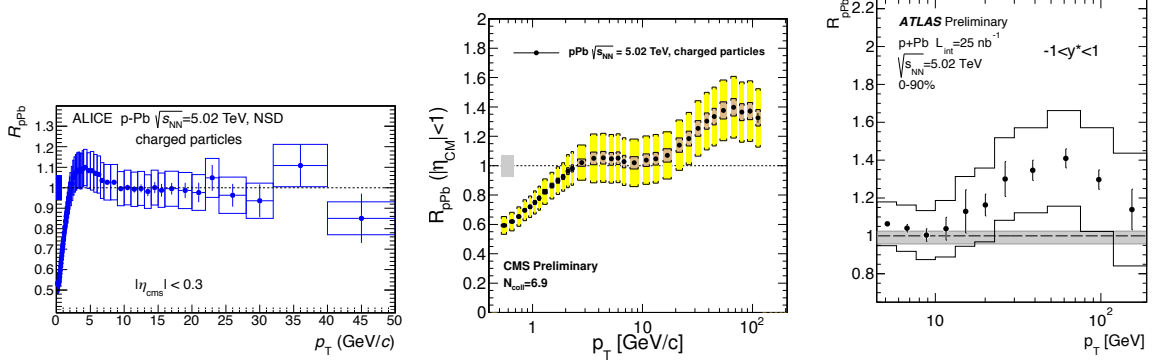


Figure 1. Charged hadron R_{pPb} at $\sqrt{s_{NN}} = 5.02$ TeV from ALICE [4], CMS [5] and ATLAS [8] (from left to right).

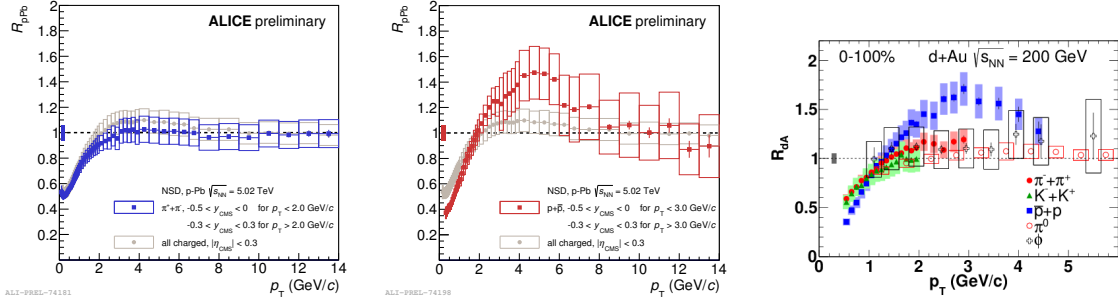


Figure 2. R_{pPb} for charged pions (left) and (anti-)protons (middle) for minimum bias pPb collisions [12]. Pions are consistent with unity for $p_T > 4$ GeV/c and the (anti-)protons are enhanced by approximately 20–40% for $3 < p_T < 6$ GeV/c. Similar measurements in dAu collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in the right panel [13]. Pions are consistent with unity and (anti-)protons are enhanced by approximately 60%.

collaborations. Results from the ALICE experiment [4] do not show this excess however the p_T reach is smaller and the statistical and systematic uncertainties are large in the region where the excess is observed in CMS and ATLAS. Results from all three collaborations are shown in Fig. 1. The excess is larger than is expected from the jet data and larger and with a different p_T dependence than expected from the EPS09 [7] nuclear parton distribution functions [5]

It is notable that there is no $p+p$ data at 5.02 TeV, so there are substantial uncertainties in the $p+p$ reference, which has to be interpolated from higher and lower energy $p+p$ collisions. An analysis by CMS has found that much of the difference between the ALICE and CMS results is in the $p+p$ reference, not the pPb measurement [5]. $p+p$ running at 5 TeV is of interest to establishing the excess observed by CMS and ATLAS and is central to reducing the uncertainties which will enable more precise characterization of the charged hadron scaling. In the short term, understanding the origin of the reference differences and direct comparison of the pPb spectra are of interest. The results from ATLAS and CMS could suggest some modification to jet fragmentation in pPb . It could also suggest that there is a larger fraction of quark jets than would be expected based on $p+p$ collisions. That might create an excess because of the softer fragmentation of gluon jets than quark jets, but it has not been demonstrated that this would be able to account for the size and p_T dependence of the charged hadron excess.

Centrality in $p+A$ collisions has been measured by the forward energy in the nucleus going direction [9, 6, 10]. The centrality dependence of very high- p_T jet production in pPb has been measured by ATLAS [6] and they find an excess of jets in peripheral collisions and a suppression of jets in central collisions relative to binary scaling. These effects cancel to produce the R_{pPb} for minimum bias collisions that is nearly unity. This is similar to what was previously seen by PHENIX [11]. ATLAS has measured over a wide range in jet pseudorapidity and finds that for a large span in η the binary collision scaled central to peripheral jet ratio, R_{CP} follows a constant trend as a function of the total jet momentum (not p_T).

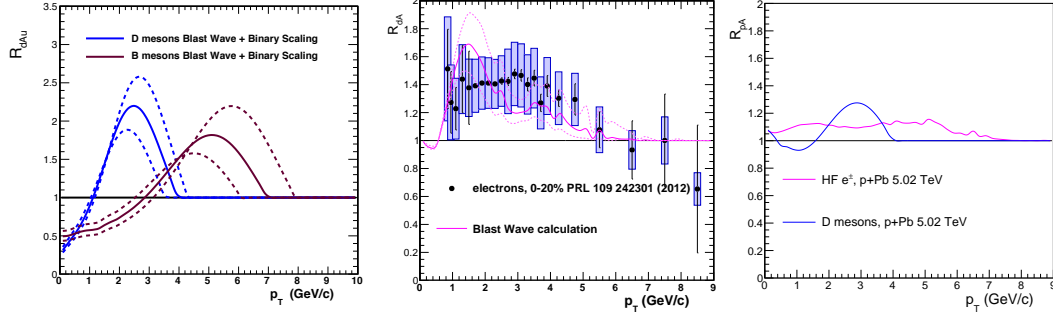


Figure 3. (left) Blast-wave expectations for D and B meson nuclear modification factors at RHIC. (center) The resulting nuclear modification factor for electrons from the decay of D and B mesons (curves) and heavy meson decay electron measurement in central $d+Au$ collisions (points) [20]. (right) The same quantity for D mesons and decay electrons at the LHC. Figures are from Ref. [21].

3. Identified Particle Measurements in $p+A$

The particle spectra at lower p_T in $d+Au$ collisions have shown an increased yield of protons and anti-protons compared to pions for $1.5 < p_T < 3$ GeV/c [14, 15]. New data from PHENIX [13] and ALICE [12] extend those measurements. The nuclear modification factors for pions and protons at both PHENIX and ALICE are shown in Fig. 2. In order to further understand the origin of the modified particle ratios, ALICE measured the $(\Lambda + \bar{\Lambda})/2K_S^0$ ratio of both inclusive particles and those associated with reconstructed jets in $p+Pb$ collisions [16]. The inclusive $(\Lambda + \bar{\Lambda})/2K_S^0$ ratio is three times larger than that which is measured in reconstructed jets. This suggests that the species dependence of R_{pA} is not associated with jets.

Since the particle species dependent modifications seem to be associated with non-jet particle production it is interesting to determine if hydrodynamics can account for the patterns in the data. The ALICE collaboration has performed blast-wave [17, 18] fits to the $p+Pb$ spectra and find the different particle species are well described by a single set of blast-wave parameters and that the extracted velocities increase as function of the multiplicity of produced particles in the collision [19].

In light of the description of light hadrons at the LHC, it is natural to ask whether this descriptions extends to $\sqrt{s_{NN}} = 200$ GeV $d+Au$ collisions¹ and heavy mesons. Results from RHIC have shown a significant enhancement of electrons from the decay of heavy mesons in 0–20% central $d+Au$ collisions [20]. If the enhancement observed in $p+A$ collisions is from a radial flow boost, then D and B mesons will be more enhanced because of their larger mass. Blast-wave fits were done to the $d+Au$ spectra in Ref. [13] and was found to give a good description of the spectra [21]. The blast-wave fit parameters from the light hadron spectra were used to determine a blast-wave prediction for the D and B meson spectra. These spectra were compared to theoretical calculations from Fixed-Order-Next-to-Leading-Log (FONLL) calculations [23, 24, 25] of D and B spectra. The resulting nuclear modification factors for D and B mesons are shown in Fig. 3 (left). In order to compare with the RHIC data which are for electrons from charm and bottom hadron decays, information about the decay kinematics from PYTHIA [26] is used. The resulting electron R_{dAu} for 0–20% central $d+Au$ collisions is shown in Fig. 3 (center) compared with the measurement from Ref. [20]. Given the uncertainties both on the data and the blast-wave parameters, the data and the calculation are in reasonable agreement. The calculations can also be done using the ALICE blast-wave parameters and the FONLL calculation at 5.02 TeV. At $\sqrt{s_{NN}} = 5.02$ TeV the harder initial mesons spectra will lead to a smaller enhancement. The resulting R_{pA} based on high multiplicity $p+Pb$ blast-wave parameters from ALICE[19] is shown in Fig. 3 (right). The data from ALICE are thus far only for minimum bias $p+Pb$ collisions so a direct comparison of the calculation to the data is not possible at this time.

In asymmetric nuclear collisions, the particle production is also asymmetric around mid-rapidity. In $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV the maximum in $dN_{ch}/d\eta$ is near $\eta \approx 2-3$ in the Au-going direction [27]. Therefore,

¹ It would also be interesting to determine if the original Cronin data [22] can be described with a blast-wave fit to see whether hydrodynamics might account for the Cronin effect.

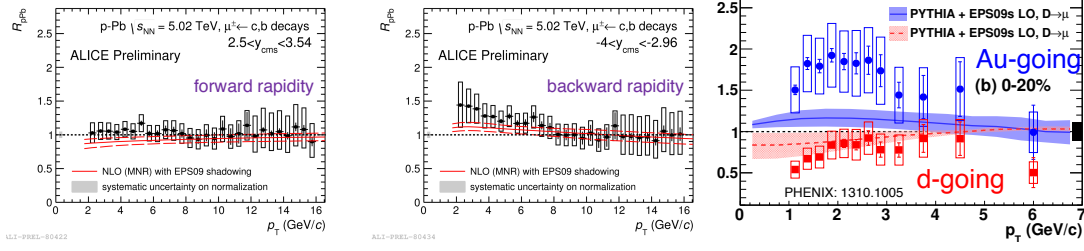


Figure 4. Nuclear modification factors for μ^\pm from heavy meson decays. Left and middle panels show R_{pPb} for forward (left) and backward (middle) in minimum bias $p+Pb$ collisions [28] and the right panel shows forward (squares) and backward (circles) R_{dAu} in central $d+Au$ collisions [29]. Curves on all panels show expectations from EPS09 [7], directions in $p+Pb$ collisions, and Ref. [29].

effects which are sensitive to the bulk particle production would be expected to also be strong in this region as well. Correspondingly, in the d -going direction where there is less particle production, these effects would be expected to be reduced. ALICE [28] and PHENIX [29] have measured muons from the decay of heavy mesons on both sides of midrapidity, in addition to the midrapidity electron measurements discussed above. The results are shown in Fig. 4. Both experiments observe an enhancement in the nucleus-going direction (denoted as “backward”), which is perhaps somewhat larger in PHENIX than in ALICE though the systematic uncertainties are large on both measurements. In the proton-going direction (denoted as “forward”) ALICE observes an R_{pPb} consistent with unity while PHENIX observes a small suppression in the d -going direction. The curves in Fig. 4 show the expectations from nuclear PDFs [7, 30]. The enhancement in the Au-going direction at RHIC is larger than is expected from EPS09s and the d -going R_{dAu} is consistent with EPS09s expectations. In ALICE, the enhancement in the Pb-going direction is perhaps slightly larger than the expectation from EPS09, though the uncertainties on the data are large.

$p+Au$ running at $\sqrt{s_{NN}} = 200$ GeV is expected in 2015. Since the $d+Au$ data taking in 2008 silicon vertex detectors have been installed in both STAR and PHENIX. This will enable the separation of decay electrons from charm and bottom which will be sensitive to whether there is the mass dependence characteristic of radial flow as well as better comparisons to nuclear parton distribution functions and LHC data. Direct reconstruction of D mesons has been done at ALICE [28]. D mesons have been measured at RHIC with the 2003 $d+Au$ data [31] and higher statistics measurements would be of great interest at RHIC both in $p+Au$ and $d+Au$.

4. Azimuthal Correlations in $p+A$

The interest in azimuthal correlations in $p+A$ collisions began with the observation of a long range correlation in pseudorapidity of particles close together in azimuth, *the ridge*, in $p+Pb$ collisions [32]. The ridge has been understood in heavy-ion collisions as being due to azimuthal correlations from the initial geometry of the collision followed by hydrodynamic evolution. The discovery of a ridge in $p+A$ collisions was immediately suggestive of collective behavior. The discovery that there was also an away-side ridge under the recoiling jet peak [33, 34] and that the correlations were larger in $d+Au$ collisions than in $p+Pb$ collisions [35] strongly suggested that the correlations were caused by hydrodynamic flow as is the case in nucleus-nucleus collisions. Another possible explanation is that the back-to-back correlations are due to Glasma diagrams in the Color-Glass Condensate [36]. Over the last year much experimental activity has gone into trying to understand the origin of these correlations. Here we highlight some new results and discuss future opportunities.

The first results of v_2 in $p+A$ systems were based on two particle azimuthal correlations. This method has several limitations. The main limitation is the influence of dijet correlations on the v_2 measurement. Additionally, this method is insensitive to the number of particles which are correlated. Here we discuss how more sophisticated techniques are being used to make qualitative improvements in the v_N measurements in $p+A$ collisions.

The most straightforward method removing dijet correlations is the *peripheral subtraction method*. In order to remove dijet correlations from high multiplicity, or central events, the correlations are measured in peripheral events (low multiplicity events). The peripheral subtraction technique relies on the assumption that modifications to jet correlations are small compared to the correlations attributed to v_N . On the near side, sensitivity to this effect can be reduced by increasing the η separation between the particles. On the away side the jets are not well correlated in η ,

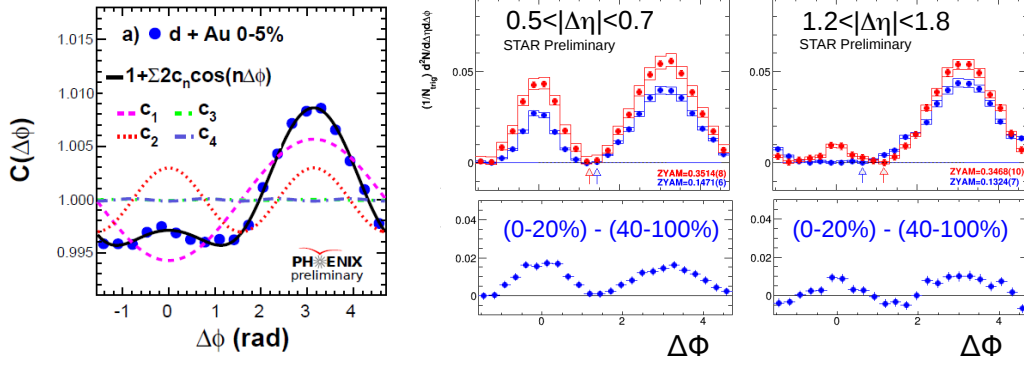


Figure 5. (left panel) Correlations of the E_T measured by the d-going and Au-going MPC detectors 0–20% central d +Au collisions. A ridge correlation is seen for $|\Delta\eta| > 6$. (top row, right two panels) Azimuthal correlation for 0–20% central events (light points) and 40–100% central events (dark points) for two different $\Delta\eta$ selections: 0.5–0.7 (middle) and 1.2–1.8 (right). The background has been subtracted using the zero yield at minimum technique [39]. (bottom row, right two panels) Results of a peripheral subtraction of the corresponding upper panels. Excess at $\Delta\phi \approx 0$ and $\Delta\phi \approx \pi$ are seen in all $\Delta\eta$ ranges (there is a downward shift in the right panel). Plot is from Ref. [40]. It should be noted that the centrality selections used here are not the same was used in Ref. [35].

so regardless of the η separation between the particles the away side jet contribution to two-particle correlations is approximately constant. The measurement is then sensitive to differences in the dijet correlations between central and peripheral events.

This limitation is particularly applicable to the first measurements of v_2 in d +Au collisions [35]. There the required η separation was between 0.5–0.7, limited by the size of the PHENIX charged particle acceptance. This separation is not enough to completely exclude the near side jet. In contrast, the LHC experiments and STAR have a wider midrapidity charged particle acceptance in η allowing more complete suppression of the near side jet correlations.

While at midrapidity PHENIX has a limited accessible $\Delta\eta$ range for charged particles, long range correlations have been shown between midrapidity charged hadrons and the energy in the Au-going muon piston calorimeter (MPC) [37, 38]. A ridge has also been observed in energy correlations between the Au-going and d-going MPCs with $|\Delta\eta| > 6$ [38], as seen in Fig 5. PHENIX has used the Au-going energy to determine an event plane in d +Au collisions and measure the v_2 of charged hadrons near midrapidity with respect to this plane [37]. The event plane v_2 results are slightly lower than the two-particle correlation results in Ref. [35].

The STAR detector has the ability to measure over a wider range in pseudorapidity separation. Results for central and peripheral correlations for a single p_T selection and two $\Delta\eta$ selections are shown in Fig. 5. Following a peripheral subtraction near and away side correlations are observed in correlations with $|\Delta\eta|$ up to 1.8. In this $\Delta\eta$ range the near side jet is completely removed in 40–100% peripheral collisions and a small near side correlation is observed in 0–20% central collisions. In order to explore the possible effects of dijet modifications between the jets in central and peripheral collisions, STAR introduced a scaling factor to match the near side jets in the small $\Delta\eta$ region. Applying this scaling factor to different $\Delta\eta$ selection causes the away side correlation to be reduced. There was discussion that this finding was inconsistent with the observation of collective effects in d +Au collisions. This conclusion is premature. A study of the sensibility of this rescaling procedure in more p_T bins is called for. Additionally, the validity of the peripheral subtraction method with a wide central bin (0–20%) and a rather central “peripheral” bin (40–100%) is not clear and has not been demonstrated. Given the focus of the community on the topic of angular correlations in very small collisions, these and related studies should be given a high priority. The ATLAS collaboration has employed a similar technique [41], but both ridges remain. A fuller understanding of this procedure requires a systematic study as a function of p_T , centrality, and η acceptance (the ATLAS η acceptance is much wider than that of the STAR detector).

Two-particle correlations alone are not sensitive to whether many or a few particles (for example as is the case with jets) are correlated. In the Color-Glass Condensate model only a few particles in the event should be correlated by the Glasma diagrams, whereas if hydrodynamics is the source of observed correlations all of the particles should be correlated. The event plane results discussed above suggest that many particles are correlated rather than just a

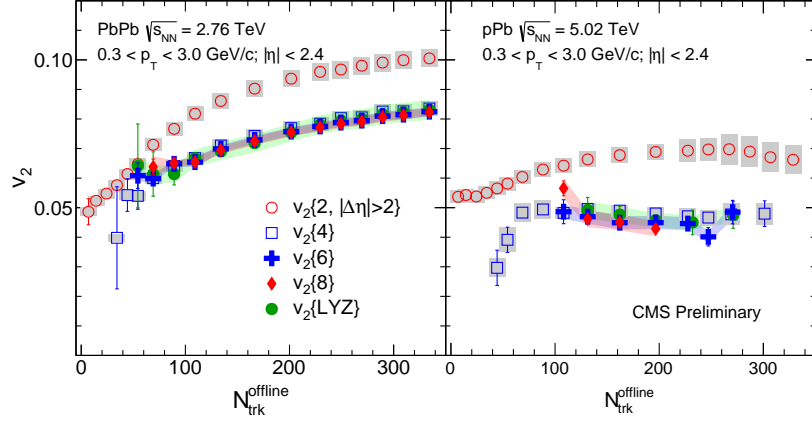


Figure 6. v_2 in Pb+Pb (left) and p+Pb (right) collisions as measured with 2, 4, 6 and 8 particle cumulants as well as the Lee-Yang Zeros method [42]. The v_2 values are plotted as a function of the number of offline tracks as measured by CMS.

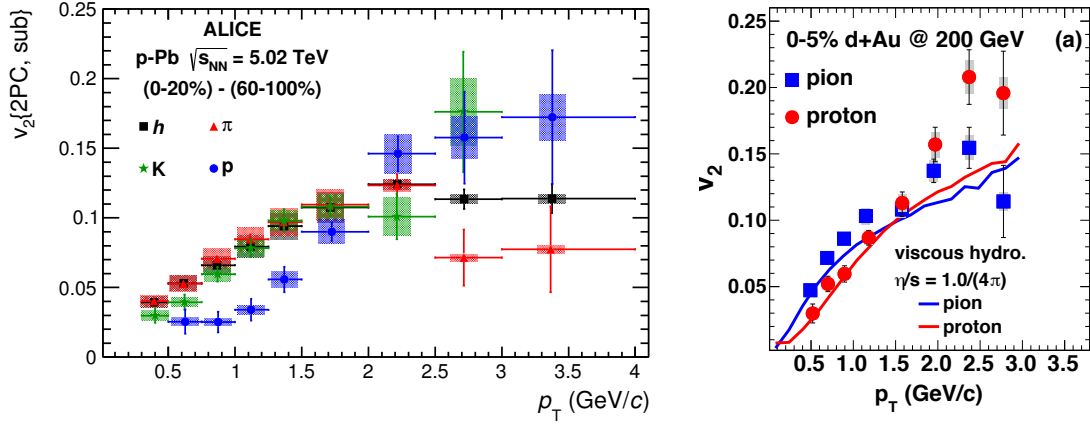


Figure 7. v_N for π^+ and p, \bar{p} for high multiplicity p+Pb collisions from ALICE [44] (left) and central d+Au collisions from PHENIX [37] (right). Shown on the PHENIX data is a hydrodynamic calculation from Ref. [45].

few. At the LHC, CMS has investigated this by measuring v_2 with cumulants. Results for Pb+Pb and p+Pb are shown in Fig. 6 [42]. The v_2 from two particle correlations with a rapidity separation between the two particles is found to be larger than the $v_2\{4\}$ (v_2 as measured via four particle cumulants). However increasing the order of the cumulants from 4 to 8 does not change the observed v_2 in either Pb+Pb or p+Pb. Additionally, CMS has extracted v_2 from the Lee-Yang Zeros method [43] which involves correlations among all the particles in the event. The v_2 extracted via that method is also found to be consistent with the cumulant v_2 for four or more particles. These results are consistent with the origin of the correlations in hydrodynamic phenomena and is not the behavior that is expected from the Color-Glass Condensate where only a few particles would be expected to be correlated.

Radial flow, in addition to modifications of the particle spectra discussed in Section 3, should also affect the v_N of hadrons in a mass dependent manner. Measurements of v_2 for pions and (anti-)protons are now available in both p+Pb (using the subtraction method) [44] and d+Au collisions (using the event plane method) [37] and are shown in Fig. 7. In both collision systems, the mass ordering of v_2 characteristic of radial flow is observed. The splitting is larger in p+Pb collisions, consistent with larger radial flow in p+Pb collisions. A hydrodynamic calculation [45] is able to qualitatively describe both the p+Pb and d+Au results. However, the magnitude of the observed splitting in p+Pb collisions is larger than that expected within the calculation.

If the correlations observed in p+A systems are a response to the initial collision geometry, then changing the

projectile nucleus should be able to change the measured v_N . This was seen in d +Au collisions where the v_2 in central d +Au collisions was found to be larger than in p +Pb collisions [35] possibly due to the initial elongated shape of the deuteron. Pursuing that idea further, it might be possible to observe a large v_3 by colliding a triangular nucleus with a large nucleus. In the time since this conference, RHIC has successfully delivered ^3He +Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Hydrodynamic calculations show some increase in the expected v_3 of these collisions compared to d +Au (in d +Au no significant v_3 has been observed [35, 37]), especially in very high multiplicity events where the ^3He nucleus could preferentially be oriented to maximize the triangularity of the collision region [45]. As a further comparison, p +Au running at RHIC is expected in 2015. The full collection of these three small nuclei collided with Au will provide the most constraining tests as to the correlations between the geometry of the initial state and the final state correlations.

5. Conclusions

There has been great interest in determining the role that hot nuclear matter effects play in p +A collisions. A wealth of new measurements were presented at this conference aimed at precisely this question. The available data strongly suggests that the angular correlations observed in these small collision systems involve many (or all) of the particles in the event, persist to large pseudorapidity separations and are related to the collision geometry. The results from single identified particle measurements support this interpretation. Mass dependent enhancement in the R_{pA} measurements has been observed and there are hints that this may extend to the heavy mesons. The modifications to the particle composition does not seem to originate in jets, but rather in non-jet particles.

The similarity of all these measurements to what has been seen in heavy-ion collisions is striking and suggests a common origin of phenomena in both systems. There was much discussion at the conference on whether hydrodynamic models could explain the totality of the data small and large system data. First attempts at more comprehensive calculations are being made [46] and more work is clearly necessary. The ability to quantitatively extract η/s from the central heavy-ion data will be unconvincing without a clear understanding of the applicability of hydrodynamics in small collision systems. Since smaller collision systems can create less matter and will live for a shorter period of time they potentially provide a good place to discriminate between models of the collision at very early times. Upcoming ^3He +Au and p +Au data to be taken at RHIC will be key to experimentally constraining the physics of small collision systems.

While much of the interest in p +A has focussed on low- p_T physics, high p_T physics of hadrons, jets, other hard probes and the centrality dependence of their production has also been of great interest. Effects are seen which are larger than expected from nuclear modifications to the parton distribution functions, the origin of which is not understood. Some of these effects are seen in the centrality dependent results and further investigation of the centrality determination in p +A and the correlations between that determination and the measured hard probes are under investigation. The comparison between p +Pb collisions at the LHC and the upcoming p +Au collisions at RHIC will be of great interest. In contrast to heavy-ion collisions, no evidence for jet quenching in p +A has been observed.

p +A systems have proven to be much more interesting and surprising than originally envisioned and might be providing the most discriminating opportunity to push our understanding of collective behavior in heavy-ion physics to its limits. Other surprising effects remain unexplained. Upcoming p +A and ^3He +Au running at RHIC as well as more p +Pb measurements will provide more insight into the physics of asymmetric nuclear collisions.

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